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THE SUN AND THE WEATHER[1]

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SMITHSONIAN INSTITUTION

"CHANGEABLE as the weather," we say, when the roaring gale follows hard on the heels of a cloudless day. But from another point of view the wonder is that weather changes disastrous to life occur so seldom. Experiments indicate that the higher forms of plants can not grow where temperatures remain continuously below 0° or above 50° C. (32° and 122° F.). These are extremes, and most food plants can only thrive within much narrower ranges. Wheat and maize are grown within the belt whose mean yearly temperature lies between 4° and 20° C., oats and barley —2° to 20° C., rice 20° to 30° C., and potatoes 2° to 16° C.

Despite these limiting conditions, no migrations of men seem to have been forced by climatic changes within historical times, extending over 5,000 years, and there is no evidence to show that the habitats of food plants have altered their latitudes during this interval. Geological evidence, however, indicates that such changes and accompanying forced migrations have occurred in past ages, but probably not of great magnitude within intervals of 5,000 years.

To bring out more strongly this remarkable constancy, in a recent paper Sir F. Stupart says:

> One of the arguments in favor of stability of climate, first used by the Danish botanist and meteorologist Schouw, is as follows: In order that dates shall come to maturity the mean annual temperature must be at least 69° F. (20.6° C.). On the other hand, the vine can not be profitably cultivated when the mean annual temperature exceeds 72° F. (22.2° C.). . . . The palm and vine grew together in Palestine in the days of early biblical history, and they both grow in the same district to-day. . . . That the rainfall of Palestine has not changed in 2,000 years receives confirmation from some measures of rainfall recorded in the Mishnah. . . .

The temperature of the earth depends almost wholly on the balance of two energies. First is the incoming energy of the sun's rays, both visible and invisible, second is the outgoing energy of the earth's rays. These latter are wholly invisible to the eye, and can only be detected by thermometric appliances.

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The fundamental nature of earth rays, however, in no way differs from that of light. The only difference resides in their wave-lengths. Light-waves range from 0.0004 to 0.0008 millimeter, earth-ray waves from 0.004 to 0.050 millimeter. The hotter the earth's surface becomes, the more copiously it emits these long-wave rays, so that at a certain temperature of the earth its output of energy to space equals its income, which is almost wholly from the sun. Solar rays lie chiefly between 0.0003 and 0.003 millimeter in wave-length, although extending feebly to very long-wave regions.

Neither sun-rays nor earth-rays pass freely through the atmosphere. Clouds, dust, water-vapor, carbon-dioxide, oxygen, and even the molecules of the air—all hinder the passage of the solar rays. Approximately 40 per cent. are reflected away to space without tending in the least to sustain the terrestrial temperature. Of the remaining 60 per cent. about one fifth, or 12 per cent., is absorbed in the atmospheric water-vapor, so that its heat is distributed through the atmosphere from a level of five miles or more down to sea-level; and about two fifths, or 24 per cent., are absorbed in clouds, principally between levels of one and two miles. Thus it seems that little more than 20 per cent. of the sun-rays intercepted by the earth as a planet are absorbed directly to produce heat on its solid and liquid surface.

An even greater atmospheric obstruction occurs to terrestrial rays. Of the output from the earth's surface, about half is absorbed in clouds, and three fourths of the remainder in water-vapor and carbonic-acid gas of the atmosphere, so that hardly more than 10 per cent. of the radiation of the earth's solid and liquid surface escapes directly to space. By successive radiations from place to place within the atmosphere, the energy does at length reach high levels where it is more free to escape from the earth. Yet the atmosphere plays strongly the part of the blanket upon the couch, or the asbestos covering upon the steam pipe, or still more accurately the glass cover over the hot-bed. In consequence of this blanketing effect of the atmosphere the mean surface temperature of the earth is probably 30° C. (54° F.) warmer than it would be if terrestrial rays passed freely from the earth's surface to space. Not only so, but the change of temperature between night and day is very greatly reduced by the same agency.

Experiments of Lord Rosse, Langley and others showed that in the brief period of a few hours during a lunar eclipse the moon's surface falls from a temperature well above freezing, even perhaps approaching that of boiling water, to a temperature far below freezing. As the moon is situated similarly to the earth as regards solar distance, but lacks an atmosphere, we readily see from this observation the great value of our atmosphere to equalize temperature. On the earth the maximum range caused by night and day, even in deserts, rarely exceeds 20° C. At most stations the mean daily range is less than 10° C.

Dependent as we are on food crops, which in turn depend on restrictions of temperature range, it seems safe to conclude that human life would be impossible here if it were not for the tempering action of clouds, water-vapor and carbon dioxide, in restraining so strongly the escape of radiation from the earth's surface. These constituents of the atmosphere make hardly 3 per cent. of its weight, but they are the all-important agents for this purpose. Oxygen and nitrogen play little part in restraining terrestrial radiation, though they scatter the incoming shorter wave-length solar rays powerfully, and thus produce the brightness and blue color of the sky.

Many years ago Professor Hann, of Vienna, published an investigation of the variability of mean daily air temperatures from day to day. Ninety stations well distributed over the earth were considered. It may be said, speaking roughly, that the region of United States and Canada from the Great Lakes to the Coast Range, and from the Ohio River to Hudson Bay is twice as variable in climate as any other large area of the inhabited world outside of Asiatic Russia. But as shown in the accompanying table, when we consider the changes on a percentage basis, measuring our departures from the absolute zero where temperature begins, we get an impression of extraordinary stability rather than of changeableness. So great a degree of stability compared with the variableness of other quantities such as length of life, stature, weight and wealth of individuals is indeed almost unexplainable, in view of the variable elements we have been considering, on which temperatures depend. Despite variable screening substances which cut off 80 per cent. of incoming heat and 90 per cent. of outgoing heat, mean daily surface air temperatures in most parts of the world rarely vary 1 per cent. from day to day.

As we have seen, the complete cutting off of solar radiation at night by no means causes the earth's surface temperature to fall to the absolute zero. This is because the darkness does not last long enough to permit the escape of more than a small fraction of the available heat of the earth. We have mentioned the powerfully hindering atmospheric constituents which cut down the rate of loss of terrestrial heat, and now we may note conditions which govern the quantity of heat available to escape.

Average Number of Days per Year in Winter, Spring, Summer and Autumn when occur Variations of Mean Daily Temperature between Certain Limits expressed in Degrees C. and also in Percentages of Absolute Temperature (where Freezing is 273° Abs. C.).

Station	Limits		Number of Days in			
	Degrees C.	Percentage	Winter	Spring	Summer	Autumn
Leavenworth, Kansas.......	0°.0 to 1°.5	0.0 to 0.5	21	24	29	26
	1.5 to 3.0	0.5 to 1.0	17	20	24	21
	3.0 to 7.5	1.0 to 2.5	29	32	25	30
	7.5 to 15.0	2.5 to 5.0	20	15	4	13
	over 15.0	over 5.0	3	1	0	1
Paris, France...............	0.0 to 1.5	0.0 to 0.5	42	46	45	46
	1.5 to 3.0	0.5 to 1.0	28	28	28	28
	3.0 to 7.5	1.0 to 2.5	19	17	18	16
	over 7.5	over 2.5	1	1	1	1
Sydney, Australia..........	0.0 to 1.5	0.0 to 0.5	50	45	47	58
	1.5 to 3.0	0.5 to 1.0	25	24	24	23
	3.0 to 7.5	1.0 to 2.5	15	19	19	10
	over 7.5	over 2.5	0	3	2	0

Available terrestrial heat varies greatly with the locality. On the water the surface layers, if above 4° C. (39.2° F.) in temperature, contract by cooling, and becoming more dense sink down and are replaced by warmer water from below. Hence a great depth of water, at least 10 meters (33 feet), is available to give up heat. Moreover, the capacity for heat of water is very high, so that a given weight of water gives up about five times as much heat as the same weight of rock cooled through equal temperature difference. Furthermore, the cloudiness and humidity of the atmosphere is generally greater over the oceans than over the land. For all these reasons the daily and yearly changes of temperature are relatively very small over the oceans.

On land, especially desert land, the available heat is much less. No exchange of warm for cooled material being possible, heat can only flow from beneath the surface by conduction. Soil and rock are such very poor conductors that no appreciable change of temperature takes place between night and day on land below a depth of 50 centimeters (20 inches). On account of this, the heat available to escape during the night over a land surface resides almost as much in the atmosphere as in the earth, unless the soil is very wet, so that oceanic conditions are to some extent duplicated. We see, therefore, the explanation of the great difference between oceanic and continental climates. The former have much the smaller changes of temperature from day to night and from summer to winter. Compare, for instance, the mean hourly and monthly temperatures of Timbuctu and Port au Prince, stations of nearly equal latitude.

MEAN HOURLY DEPARTURES FROM MEAN TEMPERATURES C.

Hours	Midnight	2	4	6	8	10	12
Timbuctu	−4°.1	−5°.6	−6°.8	−7°.7	−2°.8	+3°.2	+6°.9
Port au Prince	−2.6	−3.2	−3.7	−3.8	−0.6	+2.9	+4.7

Hours	2	4	6	8	10	Mean	Range
Timbuctu	+8°.5	+7°.4	+3°.4	−0°.1	−2°.4	29°.2	16°.2
Port au Prince	+4.5	+3.1	+1.1	−0.8	−1.3	25.9	8.5

MONTHLY MEAN TEMPERATURES C.

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Range
Timbuctu	21°.8	23°.8	28°.1	32°.5	35°.0	34°.2	32°.7	31°.1	31°.8	31°.0	26°.8	21°.4	13°.6
Port au Prince	24.1	24.6	25.1	25.9	26.0	27.1	27.6	27.3	26.7	26.3	25.6	24.4	3.5

Thus Timbuctu in the Sahara Desert has twice the daily range and four times the yearly range of temperature that Port au Prince on the coast of Haiti does.

Besides the atmospheric blanket and the heat capacity of the surroundings, a time element affects the range of temperature changes attending fluctuations of solar radiation. A rotating disk having a sector of its surface cut away is often used to diminish the apparent intensity of a beam of light. If the disk is rapidly turned, the eye can not detect the changes from light to darkness, and *vice versa.* The effect seen is that of a light of diminished brightness. But if the speed is reduced, fluctuations become more and more noticeable, till at slow speed the full change from light to darkness is apparent. Similarly it should be with changes of the earth's temperature produced by changes of solar radiation. If the solar changes were sufficiently slow, they should produce complete and equal temperature changes at all stations, whether desert or oceanic, provided no secondary changes of cloudiness or humidity, or other variable elements, accompanied.

How large a terrestrial temperature change ought then to follow a slow increase of 1 per cent. in solar radiation?

Evidently the earth's temperature should increase until its own radiation to space becomes 1 per cent. greater. Bodies which emit radiation by virtue of their temperature are of more or less radiative efficiency, but all natural bodies fall short of the theoretical "perfect radiator." This instrument is closely approached by an enclosure with a minute opening for the escape of its radiation, and with walls of equal temperature. For the "perfect radiator" the emission is proportional to the fourth power of its temperature above absolute zero. It is known that water is very nearly a perfect radiator at ordinary temperatures, and moist soil also. Hence we shall not be far wrong in supposing that the radiation of the earth varies as the fourth power of its absolute temperature. Thus in order to increase its radiation 1 per cent. we should expect an increase of the earth's mean temperature from 287° Abs. C. to 287.7° Abs. C.; for the fourth powers of these numbers differ by 1 per cent. For very slow fluctuations of solar radiation of a few per cent. range we therefore expect 0.7 as many degrees change of terrestrial temperature as the number of per cent. change of solar radiation.

Compare this with the yearly range at Timbuctu. Taking into account the obliquity of the rays and the distance of the sun, the yearly range of solar radiation at north latitude 16° 49′ is 34 per cent. Corresponding to this we expect 24° temperature change. The actual change is 13.6° at Timbuctu. From these figures we conclude that, even for desert climates, changes of solar radiation must be of several years period to produce their maximum temperature effects. It seems probable that solar radiation changes attending the eleven-year cycle of sunspots may be sufficiently slow to produce nearly full temperature effects, not only in deserts but over the world in general.

What changes of solar radiation attend the sunspot cycle? Owing to effects of clouds, haze, humidity and dust in the atmosphere, it is not possible to determine changes in the solar emission of radiation, without using complicated apparatus and methods of observing, and conducting the research at more than ordinarily favorable stations. In short, no observations competent to determine real solar radiation changes were made prior to the year 1905. Since then suitable measurements have been conducted for several months of each year (excepting 1907) by the Smithsonian Astrophysical Observatory, at a station on Mount Wilson, near Pasadena, California. The results obtained give values of the so-called "solar constant of radiation." This is the quantity of energy per square centimeter per minute received at right angles to the solar beam in free space at the earth's mean solar distance. The following table shows the yearly mean values, usually representing about 100 days each, as obtained at Mount Wilson in the months June to October, inclusive.

SUNSPOTS AND SOLAR RADIATION

Year	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915
Solar constant...	1.956	1.942	——	1.936	1.918	1.921	1.923	1.940	1.907	1.948	1.949
Spot number....	62.5	53.8	62.0	48.5	43.9	18.6	5.7	3.6	1.4	9.7	46.0

These figures do not indicate a very close dependence between the prevalence of sunspots and the intensity of the sun's emission of radiation, yet they do seem to indicate that there is a tendency to increased radiation when the sunspottedness is rapidly increasing, or at maximum, compared with the period when the sunspottedness is rapidly declining or at minimum. Contrasting from this point of view the mean values for the years 1905–6–8 and 1914–15 with those for 1909–10–11–12–13, we have:

	5 Active Years	5 Inactive Years
Mean solar constant	1.946	1.922
Mean sunspot number	46.1	14.6

If this be regarded as typical, we learn that an increase of 25 sunspot numbers is attended by 1 per cent. increase of solar radiation. The average range of sunspot numbers in the 15 sunspot cycles from the year 1750 to the year 1906 was 90, so that on the basis just stated an average sunspot maximum might be expected to be attended with 3.6 per cent. more emission of solar radiation than the minimum of sunspot activity. This, according to our preceding conclusion, might be expected to be attended with a general *increase* of terrestrial temperature of 2.5° C.

The dependence of sunspots and terrestrial temperature has lately been investigated by the method of correlation (of which we shall say more below) by Dr. Walker, director general of the Indian Meteorological Department. His studies deal with 97 stations in all parts of the world and show that with the exception of northwestern Africa, the west and north coasts of the Eurasian continent, Bermuda, New Zealand and a part of the Indian Ocean, the world in general has *lower* temperature at sunspot maximum than at minimum. Numerical values have been obtained for a great number of stations, and for long periods of years, by several investigators, but notably by

Köppen. He finds that for the interval from 1815 to 1873 the average *decrease* of terrestrial temperature at sunspot maximum was 0.7° C., and for the interval 1873 to 1910, 0.5° C. The difference may well be attributed to the greater average intensity of the sunspot maxima in the former interval.

Here then is a well-established paradox. Increased solar activity, as indicated by sunspots, is attended by decreased terrestrial temperature. It has been suggested, but not demonstrated, that the explanation lies in an increase of cloudiness at sunspot maximum; and that the increase of cloudiness is caused by the penetration of the atmosphere to lower levels by electric ions shot from the sun with greater power at maximum solar activity.

Besides these variations of solar radiation from one year to another, the Smithsonian observations indicate fluctuations which run irregular courses, often in a week or ten days. The true solar existence of these changes has been confirmed in several ways, among others in the years 1911 and 1912 by making the measurements simultaneously in California and Algeria, separated by a third part of the earth's circumference. More recently it has been found that the changes are accompanied by variations of brightness over the sun's disk. Dr. Bauer, too, has shown that fluctuations of the earth's magnetic field accompany them.

As an example of these changes, see the following observations of September in the year 1911.

Date September	3	4	5	6	7	8	9	10	11
Solar constant value	1.888	1.906	1.917	1.960	1.938	1.993	1.948	1.908	1.892

The observed range here is 5½ per cent. in eight days. What effect should this produce on the weather?

Recalling that a change of 100 per cent. in twenty-four hours produces a temperature change of 8.5° C. at Port au Prince, and 16.2° C. at Timbuctu, while 34 per cent. change in 365 days produces 3.5° C. at the former and 13.6° C. at the latter of these two stations, we should expect that for the average station a solar radiation change ranging 5 per cent. in eight days might produce about 0.8° C., or nearly 1.5° F., temperature fluctuation. But as we have seen that for many stations the increase of solar radiation, which seems naturally to accompany the great solar activity of sunspot maximum, is attended by *lower* terrestrial temperatures, we may not be surprised if things turn out less simply than expected in regard to the short interval solar fluctuations.

The subject has lately been investigated by Dr. H. H. Clayton, of Argentina, formerly of Blue Hill, Mass. In such an investigation a natural procedure would be to make two superposed curves, one to show the change of solar radiation day after day, and the other the change of temperature. The trouble with this method is that there are so many influences that operate on the weather, apparently haphazard, that their combined effect often masks the influence under investigation. Accordingly, Dr. Clayton employed the mathematical method of correlation, which has come into general use in biological researches. In this method two functions, like the diameter and circumference of a circle, that are related so intimately that the increase of the one depends only on the increase of the other, are said to have a correlation coefficient +1. Two functions, like the heights of two ends of a balance, which are so connected that increase of one depends only on decrease of the other, are said to have a correlation coefficient —1. Between these perfect degrees of positive and negative correlation lie all degrees of dependence, and a coefficient of correlation, zero, indicates that the variables are unrelated. As in other investigations, it is valuable to determine the probable error of each coefficient of correlation, and one considers a correlation standing alone as demonstrated when its coefficient is numerically three or four times its probable error. A group of correlations may, however, so obviously support each other as to lend certainty to the correlation of individuals of the combination, though these individual members would otherwise be doubtful in view of probable error.

Dr. Clayton determined for about fifty stations, well distributed over the globe, correlation coefficients connecting temperatures with solar-constant values determined at Mount Wilson in 1913 and 1914. As he thought it likely that the terrestrial influence of solar changes would be deferred, he computed the correlations not only for identical days, but for the 1st, 2d, 3d, 4th, and 5th days thereafter. Here are examples of the largest correlation coefficients obtained.

Days Following Solar Observations..............			0	1	2	3	4	5
Station	Latitude	Longitude	Correlation Coefficient					
Pilar..........	31° 39′ S.	63° 5′ W.	0.32	0.51	0.54	0.48	0.33	0.13
San Diego.....	32° 43′ N.	117° 10′ W.	0.18	−0.10	−0.29	−0.50	−0.52	−0.44

Probable error about ± 0.07.

From this we see that at Pilar, Argentina, *increase* of temperature followed increase of solar radiation, and the maximum effect occurred after one or two days, while at San Diego, California, *decrease* of temperature followed increase of solar radiation, and the maximum effect occurred after three or four days. The coefficients of correlation at maximum are fully seven times the probable error numerically, so that the connection is well assured. For other stations different values, some positive, others negative, were obtained, ranging down to zero.

When marked on the map the stations of positive and negative correlations were found to arrange themselves very definitely in zones. Speaking roughly, in the zone within the tropics, but broadening over land areas and narrowing over the oceans, the correlation is positive, and so also in the arctic and antarctic zones, and extending down the east coast of North America. In the remainder of the world, comprising the great temperate zones, the correlation is negative.

A similar investigation, but less extensive, was made by Clayton on the relation of atmospheric pressure to solar radiation. Similar zones seemed to be indicated, but where temperatures rose after increases of solar radiation, pressures fell, and *vice versa.*

For several of the stations, Clayton's investigation indicates the actual numerical changes in temperature which follow a change of solar radiation. From the average of all the decided changes of solar radiation, I find from his curves that for 1 per cent. solar change there was 5.2° C. average change in temperature at Pilar, 1.5° C. at Manila, and 6.3° C. negative change at Winnipeg. Other stations would appear to give equally surprisingly large results. Clayton's figures, however, relate to maximum daily temperatures. It may be reasonably supposed that the changes of mean temperature corresponding to 1 per cent. increase of solar radiation would be half as great, or +2.6°, +0.75° and —3.15° C., respectively, at the three stations. We had been led to expect almost surely not more than 0.7°, and probably not more than 0.2° C.

Five thoughts are suggested by this remarkable result. First, that the figures ought to be confirmed by tests extending over other years and other stations. Second, that if confirmed they will indicate that secondary processes are set going in the atmosphere by small changes of solar radiation, which, by altering the atmospheric blanketing effect, magnify in some stations, and reverse in others the natural direct effects of the solar fluctuations. Third, that if such large changes of temperature are thus caused, investigation may be apt to reveal important effects of solar fluctuations on the winds, cloudiness and precipitation. Fourth, that since the outstanding unexplained departures from mean daily temperatures, as illustrated above for Leavenworth, Paris and Sydney, are seldom of much greater magnitude than the changes which are found by Clayton to be produced by changes in the sun, and as the maximum effects of solar changes follow from one to five days after the cause, depending on the latitude of the station, it may be possible that a very large proportion of weather changes will become predictable for some time in advance, if daily measurements of the solar emission shall be secured. Fifth, that since daily solar-constant measurements of sufficient accuracy can only be had by establishing several new observing stations in the most cloudless regions of the earth, at an initial expense of from $5,000 to $10,000 each, and continued expense of from $5,000 to $10,000 per year each, the occupation of this promising field in forecasting is likely to be deferred until after the war is over.

At present the Smithsonian Institution is alone making the required measurements, at Mount Wilson, California, and Hump Mountain, North Carolina. Weather conditions are not sufficiently favorable at either station to warrant the expectation that on half the days in the year the solar radiation will be properly measured. A projected station in South America has been deferred on account of war conditions, but may soon be occupied. A bequest of half a million dollars to the Smithsonian Institution would enable it to handle adequately this apparently exceedingly important problem.